Physics with Cold Molecules Using Buffer Gas Cooling

Precision Measurement, Collisions, and Laser Cooling

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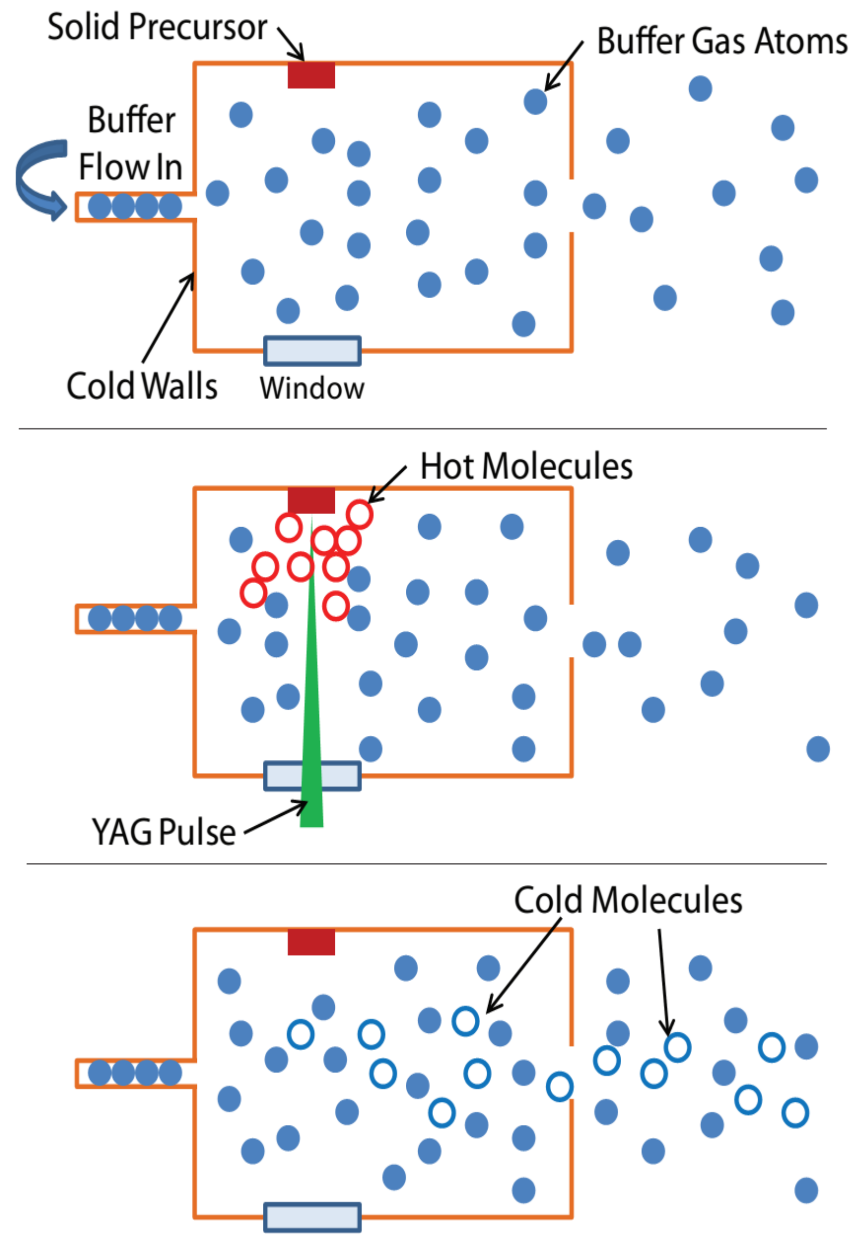
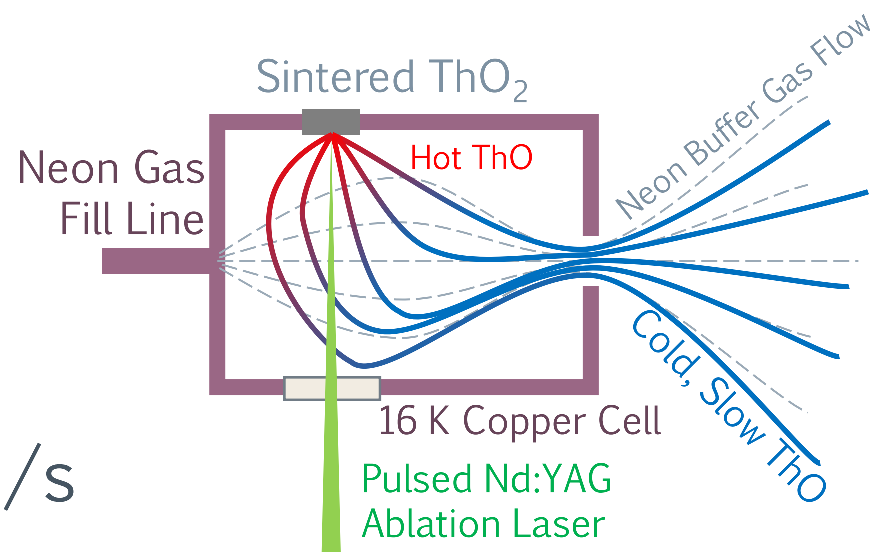
Buffer gas cooling

- Use inert gas in cryogenic environment to cool via collisions
- Can be used to make cold atoms or molecules in a cell or beam
- Highly versatile – works for radicals, refractory materials, reactive species, polyatomics,…
- Also called collisional cooling [Messer & De Lucia, 1984]
- Review: N. Hutzler, H. Lu, & J. Doyle, Chem. Rev. 112, 4803 (2012)



Hydrodynamic Buffer Gas Beams

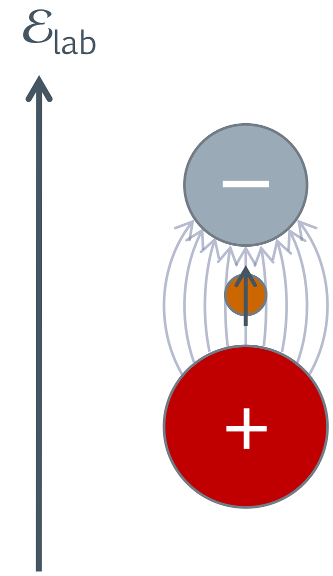
- Entraining cold species in buffer flow results in high extraction (10-40%)[1,2,3,4]
- Translationally, rotationally cold
- Velocity 100–200 m/s
- >100x brighter than comparable supersonic beams[5]



[1] S. Maxwell et al., PRL 95, 173201 (2005); [2] D. Patterson & J. Doyle, JCP 126, 154307 (2007)
[3] N. Hutzler et al., PCCP 13, 18976 (2011); [4] J. Barry et al., PCCP 13, 18936 (2011)
[5] M. Tarbutt et al., J. Phys B. 35, 5013 (2002)

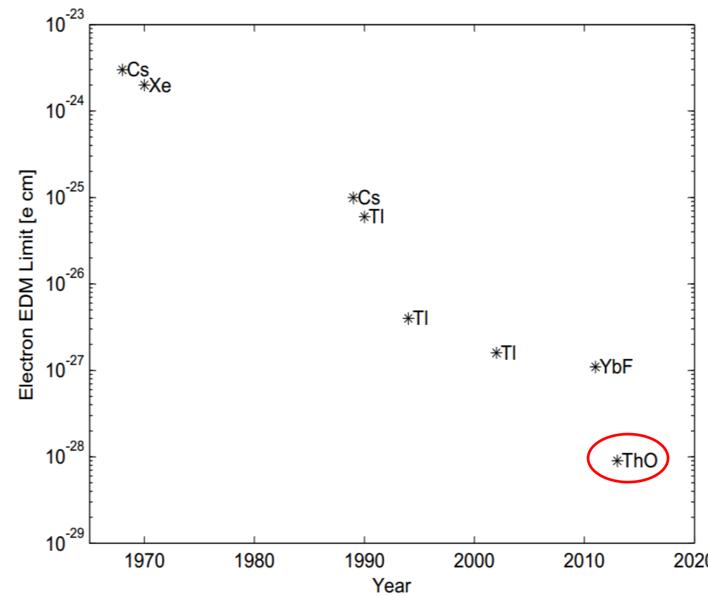
ACME Electron EDM Search

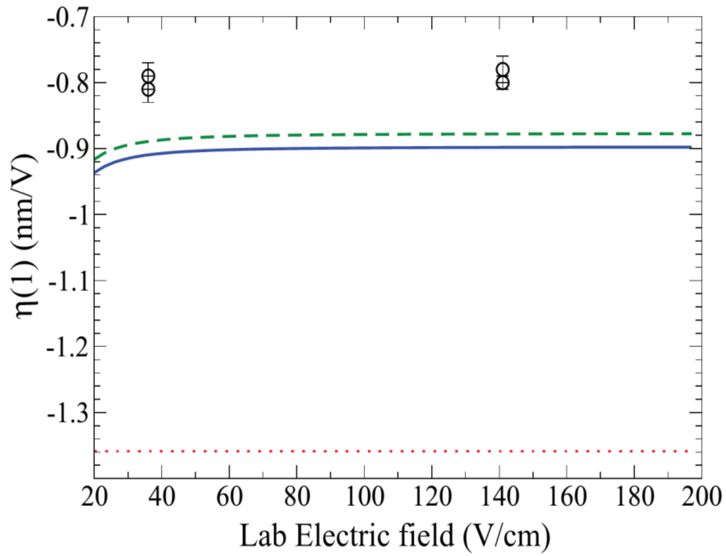
- Largest accessible electric fields are inside polar molecules
  - 10-100 GV/cm
- Look for $d_e \cdot \mathcal{E}_{eff}$ shifts in levels
- Molecules are typically heavy, reactive, radicals
  - Our molecule: ThO ($H^3\Delta_1$)
  - YbF, ThF^+, WC, PbF, PbO,…
- Slow, bright, cold beam source is desirable



ACME Results

- $|d_e| < 8.7 \times 10^{-29}$ e cm[1]
  - Ten-fold improvement[2]
  - Shot noise limited
  - Currently working on another factor of 10
- Theoretical and experimental study of Zeeman interaction
  - Effective g-factors depend on E-field, molecule orientation[3]
    Energy $\propto M\Omega|E|B$
  - $\sim 10^{-5}\ \mu_B$ at 100 V/cm
  - Measured effect at $\sim 10^{-7}$ μ_B level, agrees with calculations[4]

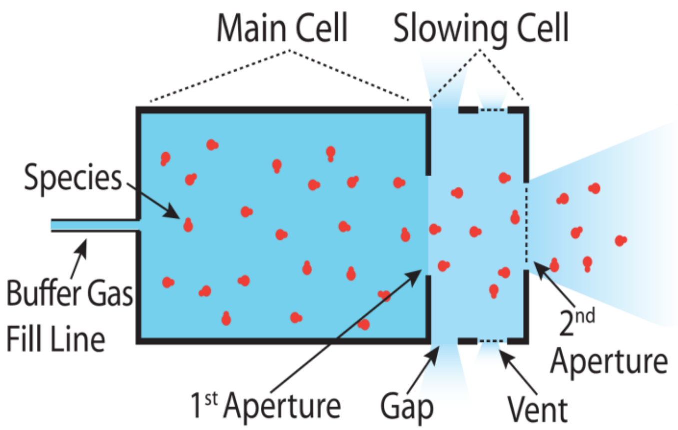


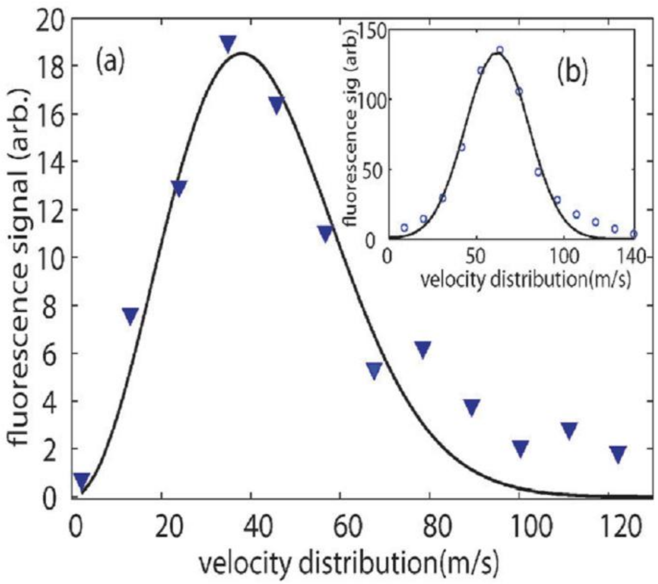


[1] ACME Collaboration, Science 343, 269 (2014) [2] J. Hudson et al., Nature 473, 493 (2011)
[3] S. Bickman et al., PRA 80, 023418 (2009) [4] A. Petrov et al., PRA 89, 062505 (2014)

Slow Beams

- Place second cell in front of beam aperture
  - Add gaps, vents to create low steady-state pressure
  - Cool to 1 K
- Resulting beam is nearly-effusive, with molecules as slow as 20 m/s[1,2]
- ~10x less intense compared to hydrodynamic beams
- Useful for trap loading
  - MOTs of Yb, Tm, Er, Ho without slowing[3]

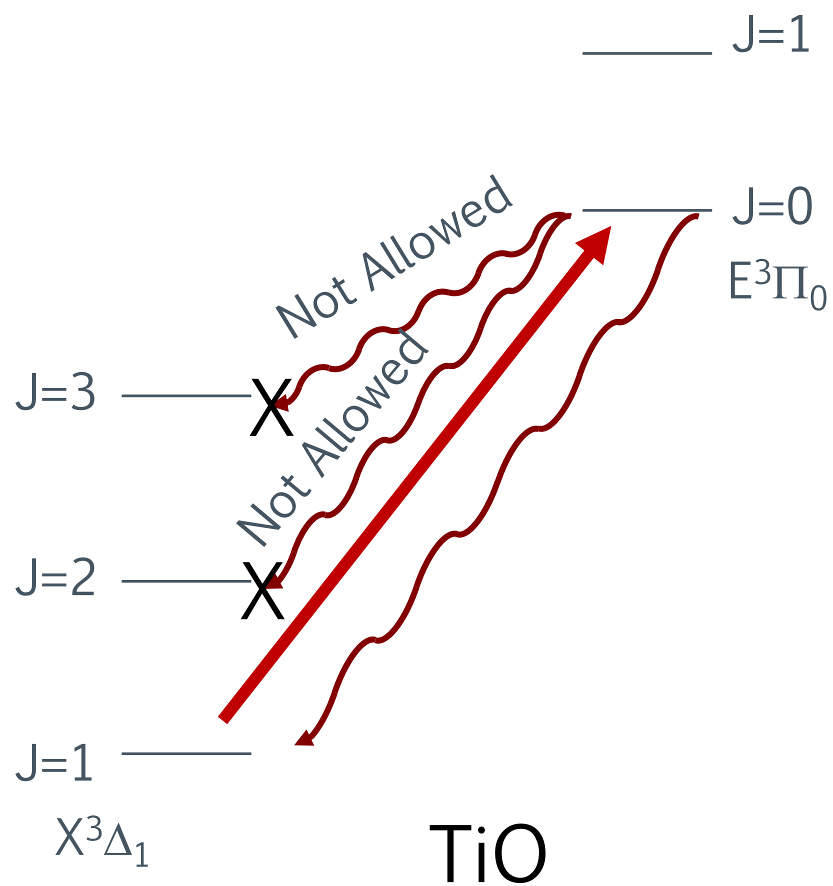




[1] D. Patterson & J. Doyle, JCP 126, 154307 (2007); [2] H. Lu et al., PCCP 42, 18986 (2011)
[3] B. Hemmerling et al., arXiv:1310.3239 , to appear in New J. Phys. (2014)

Laser Cooling Polar Molecules

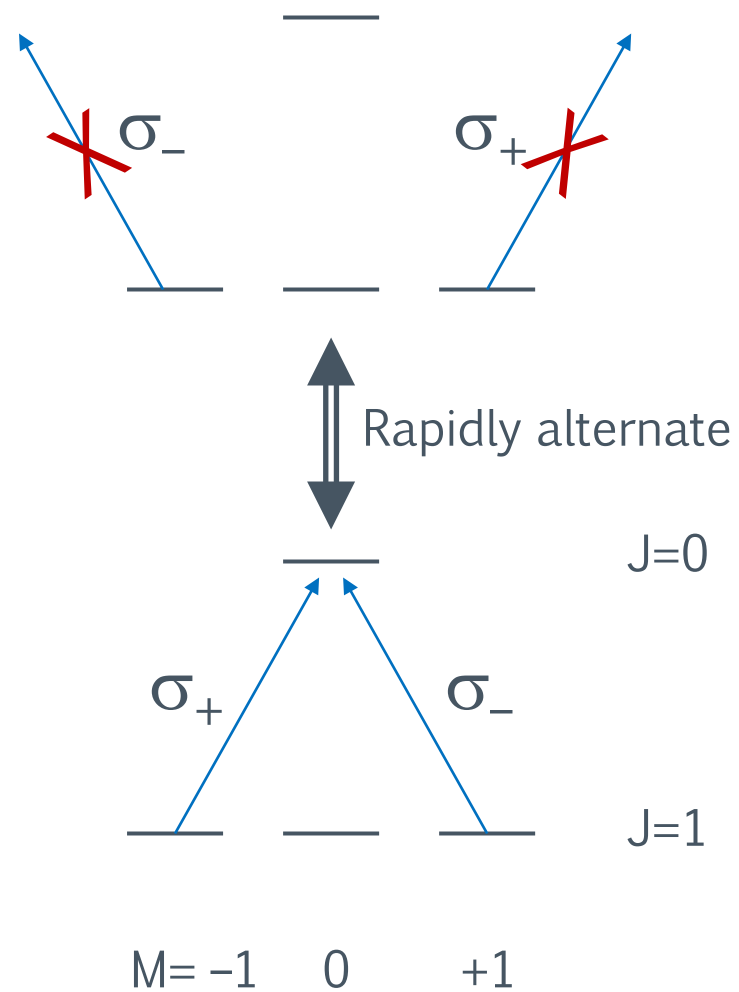
- Molecules lack cycling transitions
- Possible to find quasi-cycling transitions
  - Choose molecules with diagonal Franck-Condon factors[1]
  - Use J →J-1 transition[2]
- First realized in SrF, DeMille Group @ Yale[3] using buffer gas beam



[1]M. Di Rosa, EJP D 31, 395 (2004); [2] B. Stuhl et al., PRL 101, 243002 (2008)
[3] E. Shuman et al., Nature 467, 820 (2010)

Magneto-Optical Trapping

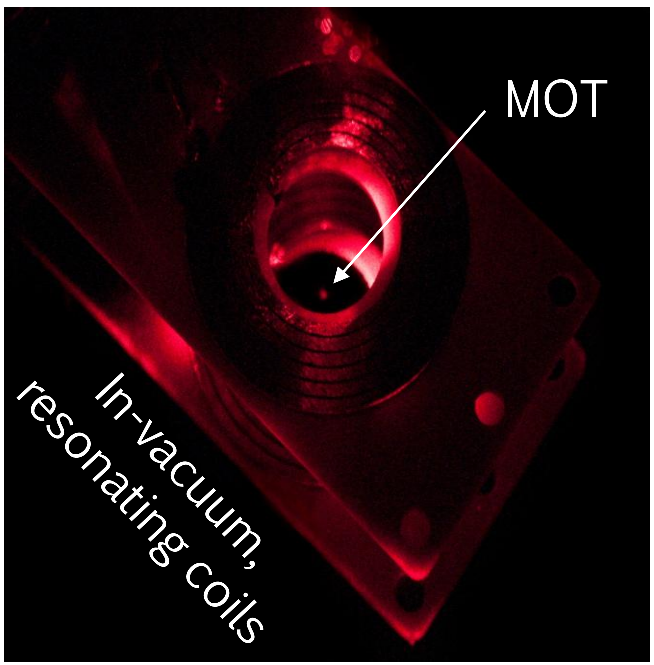
- Difficulty: J → J-1 transitions have dark Zeeman states
  - MOTs rely on scattering both circular polarizations
- Our approach: change sign of B, polarization at $\sim\gamma_{rad}$
  - Molecules cannot accumulate in dark states
  - Collaboration with Ye Group @ JILA, who first demonstrated in 2D MOT with YO[2]
- DC MOT of SrF demonstrated recently[1] by DeMille Group @Yale

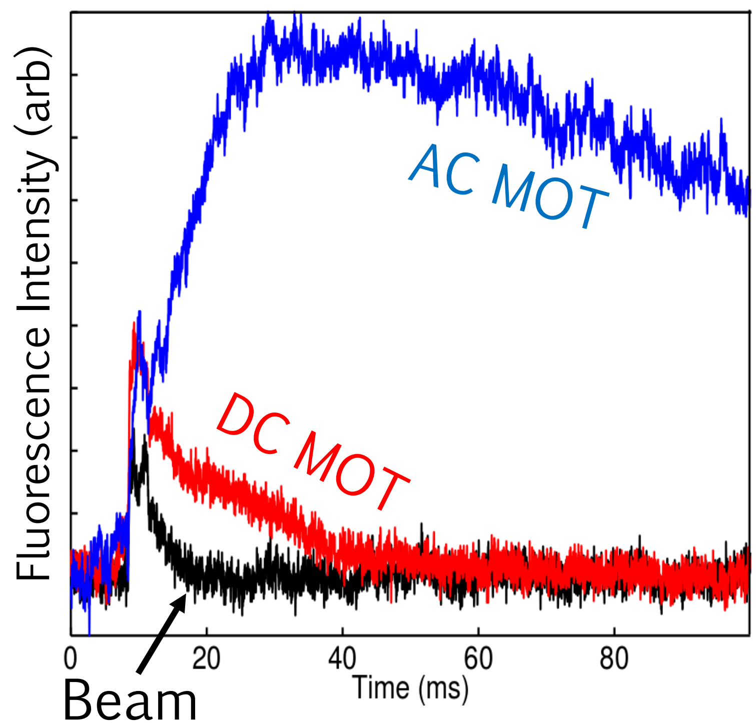


[1] J. Barry et al, arXiv:1404.5680 (2014); [2] M. Hummon et al., PRL 110 143001 (2013)

Testbed: AC MOT on ^{6}Li D1 Line

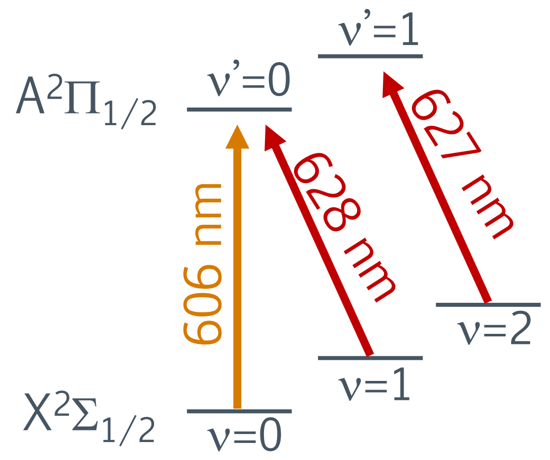
- Li D1 line has similar dark state problem ($F \geq F'$)
- AC MOT at 6 MHz yields significant increase in number, lifetime over DC MOT
  - Will this give us an improved MOT compared to SrF?

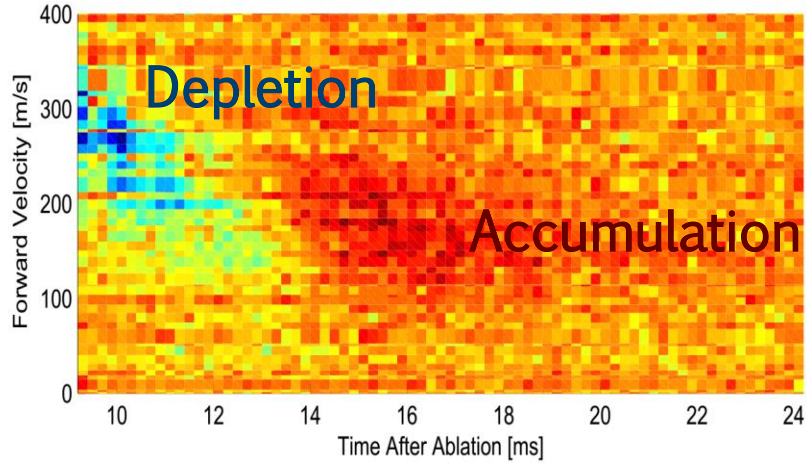




Progress Toward CaF MOT

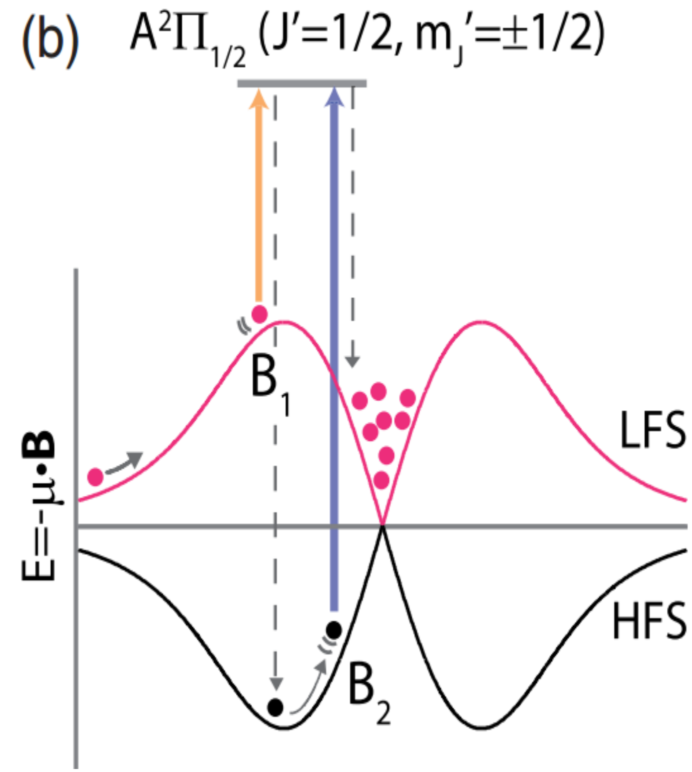
- Goal: dense, long-lived MOT of CaF
- White-light slowing
  - Recently: ~50 m/s slowing with hydrodynamic beam
  - Also demonstrated at ICL with supersonic[1]
- Next steps
  - Optimize slowing
  - Load MOT



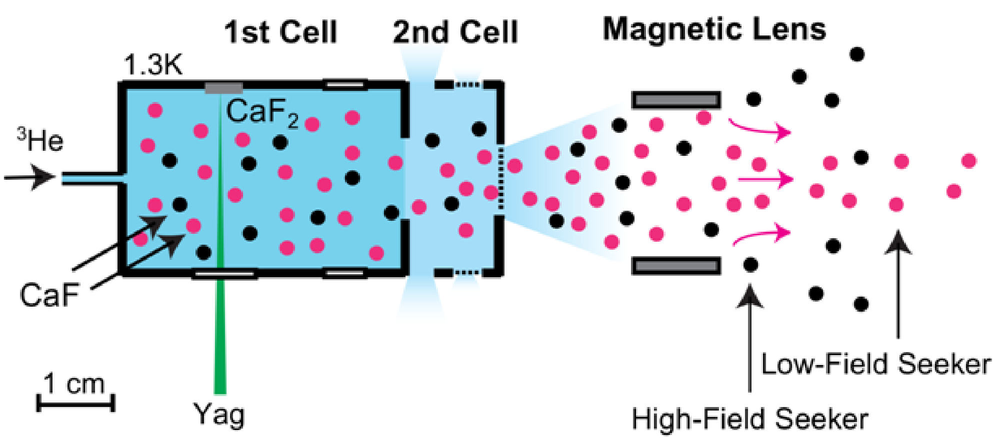


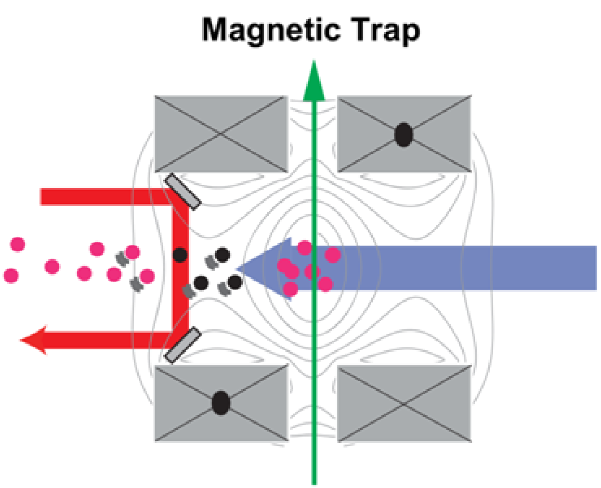
[1] V. Zhelyazkova et al., PRA 89, 053416 (2014)

Magnetic Trapping of CaF and K



- Optically pump into trapped state
  - Sufficient energy removed by climb into trap
  - General: magnetic moment, 2 photon cycles
- Recently demonstrated with CaF[1] and K

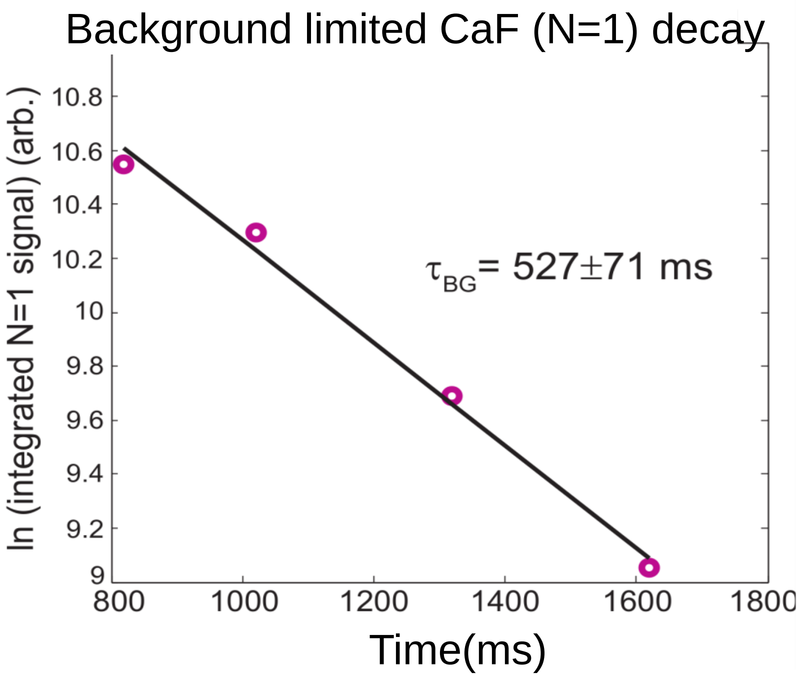


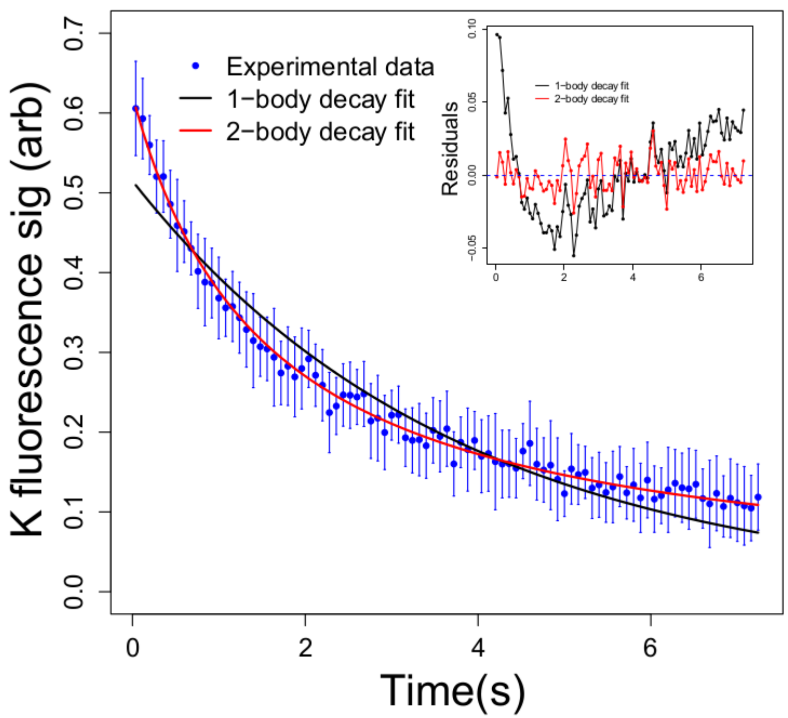


[1] H. Lu et al., PRL 112 113006 (2014)

Results

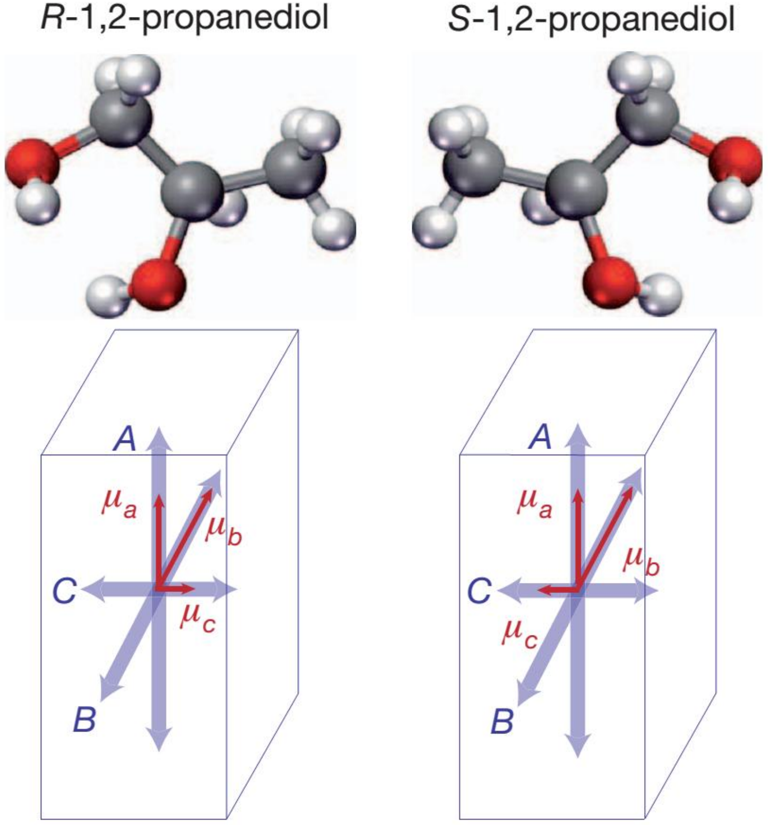
- Demonstrated trap lifetime of 500 ms for CaF, 9 s for K
- Next steps
  - Co-load atom, molecule
  - Observe collisions
  - Sympathetically cool?
- Extend to triatomics
  - Path to ultracold polyatomics?
  - Observed cold SrOH in buffer cell [Tuesday]
  - Spectroscopy from T. Steimle was a great help!





Applications with Large Molecules

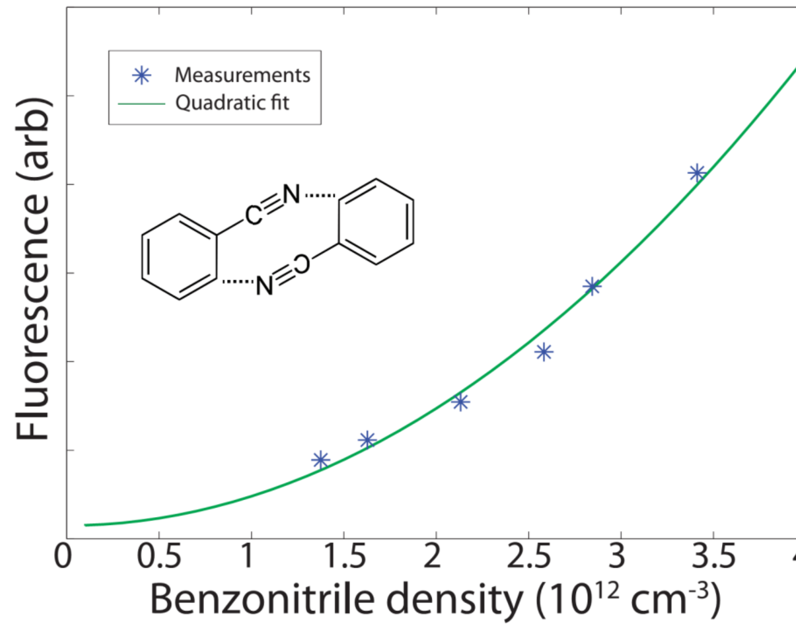
- Broadband mixture analysis
  - Cold, slow-moving, dense samples
  - Combine with optical, FTMW, double-resonance, comb, etc.
- Enantiomer-specific detection[1]
  - Fast, sensitive, widely applicable



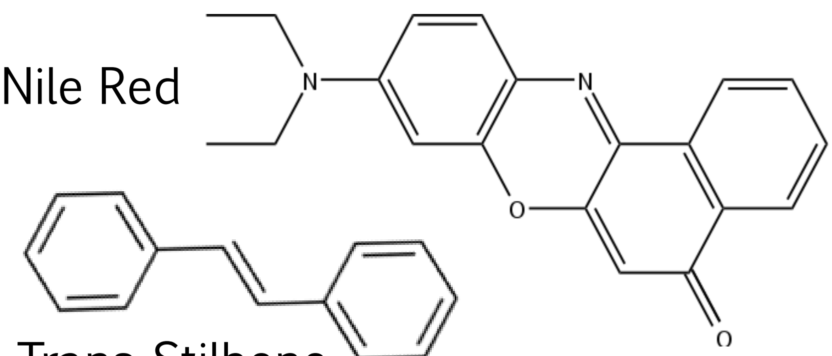
[1] D. Patterson, M. Schnell, & J. M. Doyle, Nature **497**, 475 (2013)

Large Molecules

- Recent Measurements in Benzonitrile[1]
  - Direct observation of dimer formation
- When is a molecule too large to buffer gas cool?
  - Clustering
  - Not known
  - Recently demonstrated non-sticking of Nile Red, trans-Stilbene[2]



Nile Red

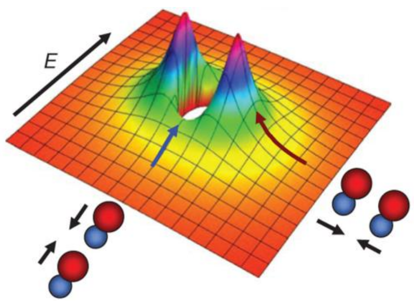


Trans-Stilbene

[1,2] J. Piskorksi et al., in preparation

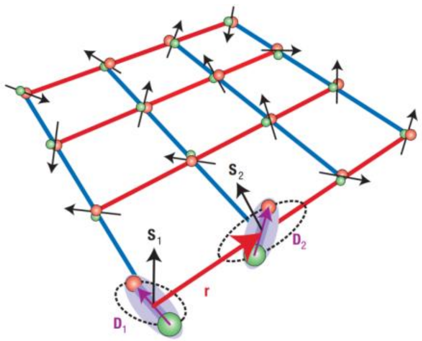
Fundamental Physics with Cold Molecules

Cold Chemistry and Collisions



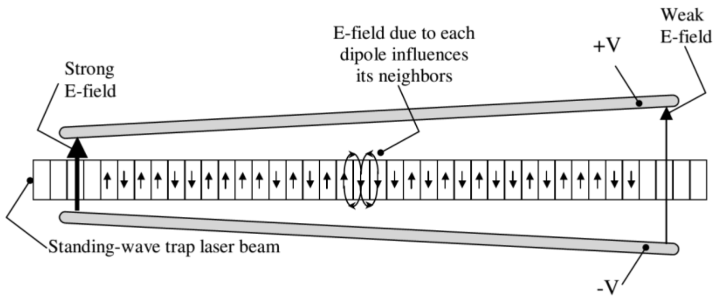
K.-K. Ni et al., Nature **464**, 1324 (2010)

Quantum Matter/Simulation



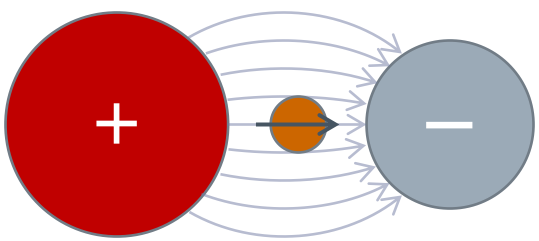
A. Micheli et al., Nat. Phys. **2**, 341 (2006)

Quantum Computation



D. DeMille, PRL **88**, 67901 (2002)

Precision Measurement



ACME, Science 343, 269 (2014)

Much more! Chemical Reviews 112 (2012)
L. Carr, D. Demille, R. Krems, & J. Ye, New J. Phys. **11**, 55049 (2009)

John Doyle's Group + Collaborators

MOT

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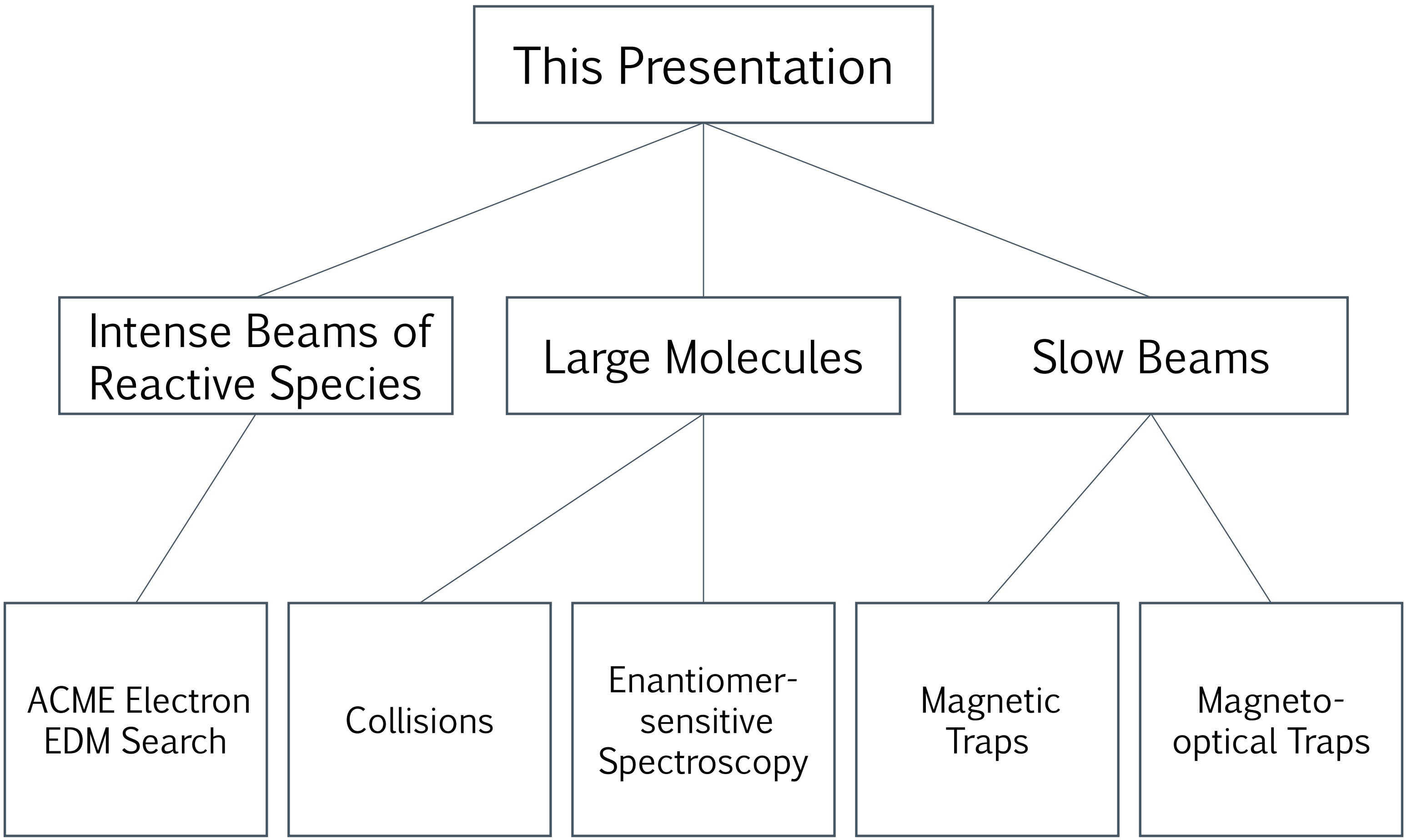
N. Hutzler, H. Lu, & J. Doyle, Chem. Rev. 112, 4803 (2012)

Harvard/MIT Center for Ultracold Atoms (CUA)
www.doylegroup.harvard.edu


This Presentation
Intense Beams of Reactive Species
Large Molecules
Slow Beams
ACME Electron EDM Search
Collisions
Enantiomer-sensitive Spectroscopy
Magnetic Traps
Magneto-optical Traps